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A SEARCH FOR EXTRAGALACTIC BACKGROUND LIGHT USING THE DARK CLOUD L134

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ABSTRACT

CCD surface photometry at 0.65 μm and single-aperture photometry at 2.2 μm on the dark molecular cloud, L134, and on nearby blank sky, were carried out at levels of 10^{-3} and less than 10^{-4} of the brightness of the night sky, respectively. Presumably because of reflected galactic light, the cloud appeared bright compared to the reference sky at both these wavelengths. Relative to blank fields, the darkest positions on the cloud had intensities, νI_ν, of 1×10^{-5} ergs cm^{-2} s^{-1} sr^{-1} at 0.65 μm and 4×10^{-5} ergs cm^{-2} s^{-1} sr^{-1} at 2.2 μm. Since the magnitude of the reflected light is unknown, one cannot deduce the level of the extragalactic background light (EBL); however, either the EBL is on the order of or smaller than these values, or the reflected light and the EBL fortuitously cancel.

Subject headings: cosmology — photometry

I. INTRODUCTION

The measurement of the diffuse extragalactic background light (EBL) would constitute a significant piece of evidence concerning two important cosmological problems: the formation and the evolution of galaxies. If during formation galaxies underwent a phase of high luminosity, as suggested by Partridge and Peebles (1967*a*) and Cox (1985), they might be visible today as a bright background of unresolved objects. A number of observers have attempted to detect this light at visible wavelengths, but thus far only upper limits have been obtained (Roach and Smith 1968; Dube, Wickes, and Wilkinson 1977; Spinrad and Stone 1978; Toller 1981). These upper limits are all on the order of $\nu I_\nu = 3 \times 10^{-5}$ ergs cm^{-2} s^{-1} sr^{-1} and, therefore, conflict with the positive result of 9×10^{-5} ergs cm^{-2} s^{-1} sr^{-1} obtained at 0.4 μm by Mattila (1976).

In some protogalaxy models there is a burst of star formation during the initial collapse of the system, resulting in a highly luminous phase. This would have occurred at high redshift and could be visible today as a diffuse infrared background in the range of 1–5 μm (Partridge and Peebles 1967*b*). Such infrared observations, however, prove to be difficult primarily because of the brighter sky background and instrumental thermal emission at longer wavelengths. The best upper limits, ~ 1–2×10^{-3} ergs cm^{-2} s^{-1} sr^{-1}, have been obtained at 2.4 μm from a balloon-borne telescope (Hofmann and Lemke 1978) and at 5–130 μm from a rocket-borne telescope (Soifer, Houck, and Harwit 1971). A tentative positive result of 10^{-3} ergs cm^{-2} s^{-1} sr^{-1} in the 2–5 μm band was reported by Matsumoto, Akiba, and Murakami (1984) from their rocket observations.

Following Mattila (1976), we used the dark molecular cloud, L134, as a dark reference field with which to compare nearby blank sky fields. To the extent that the cloud is dark and the background light is attenuated in the cloud (both of these assumptions will be discussed later), the difference between the luminosities on and off the cloud constitutes a measurement of the background light. Since L134 is relatively nearby, ~ 150 pc (see Mahoney, McCutcheon, and Shuter 1976; Mattila 1979), the background light contains radiation from unresolved stars as well as EBL.

We mapped the entire cloud to look for the darkest regions to compare with the blank fields. If the darkest part of the cloud is less luminous than the background, a positive measurement of the diffuse background can be made. If, on the other hand, the darkest region of the cloud is brighter than the background (as was the case in our measurements), it is difficult to interpret the data unambiguously as a positive result or an upper limit on the EBL.

II. OBSERVATIONS

a) 0.65 Micron (R band) Observations

An *R*-band ($\lambda = 0.65$ μm, $\Delta\lambda = 0.13$ μm) map of L134 was made with the No. 1 0.9 m telescope at KPNO in 1985 April using the 348×512 pixel RCA CCD camera. Data were read out in 4×4 pixel blocks to reduce the readout noise. Each enlarged pixel block corresponds to $3''.5 \times 3''.5$ in the sky. Thirty-two overlapping frames, each with a 2 minute integration time, were taken over a 90 minute period. Each frame overlapped half of the previous frame in a raster pattern that covered most of the cloud (see Fig. 1). Out of focus telescope dome observations were obtained as flat fields and were divided into each frame. Then high pixel values were found by three iterations of a 3 σ cut filter which effectively located the brightest pixels due to stars and galaxies. The effective radius of each bright pixel patch, determined from the 3 σ cut, was doubled, and these regions were removed from further analysis. The bright pixel locations from corresponding overlapping frames were cross-correlated to check the relative sky position of each frame. Residual gradients at the 1% level required another "flat-fielding" operation. We lacked sufficient observing time to obtain other blank-sky frames with signal to noise comparable to the average of all the data frames taken of the cloud. Thus a mean over all 32 frames with bright sources removed was constructed and used to flatten individual frames. Data frames were scaled so that the mean intensity recorded in each frame was unchanged after dividing by the flat field.

The airglow contribution to successive frames varied by as much as 20%. Because we need to obtain relative photometric observations over the entire field, we cannot fit and subtract an arbitrary low-order polynomial to each CCD frame to correct

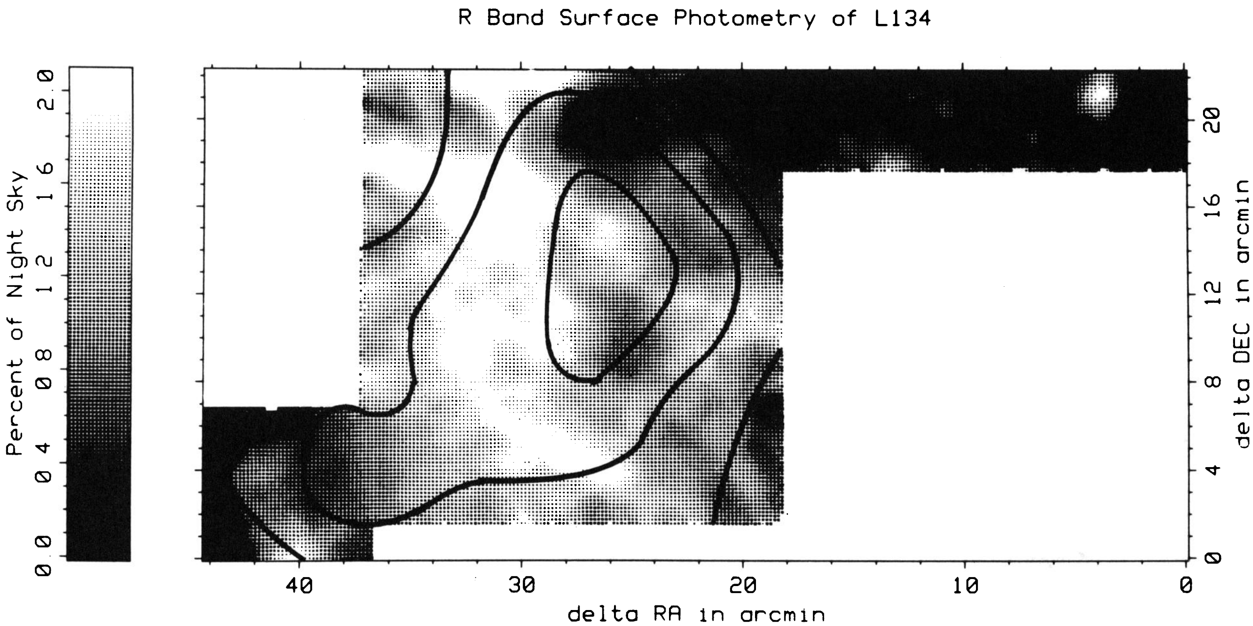

FIG. 1.—0.65 μm map of L134. Origin (0, 0) of the map is located at $15^h49^m6\overset{s}{.}9$, $-4°44'53''$ (epoch 1950). The three contours roughly correspond to star count densities at 0.09, 0.26, and 0.44 of the background density.

for the sky background signal. A least squares technique was devised which simultaneously fits a constant to each CCD frame and minimizes the error between pixels from overlapping frames. This corrects for fluctuations in sky brightness from frame to frame but not for spatial variations of the sky background within a frame. The corrected data were then combined in a mosaic map of L134. Details of the fitting procedure are discussed in the Appendix.

Two such maps were made within a 4 hr period on a single night, and over most of the area the two maps agreed to within slightly greater than 0.1% of the night sky (during the last few frames sky conditions were not photometric—some high cirrus clouds were apparent). About half of this discrepancy comes from counting statistics. It is apparent that variable inhomogeneities in the sky brightness are $\leq 0.1\%$. The secant law gradients in airglow and in the zodiacal light common to each frame are divided out by the flat frame since it contains these gradients. Because the flat frame was constructed from observations of the cloud, which has a mean spatial brightness gradient, a slight spurious gradient ($\sim 1\%/0\overset{\circ}{.}5$) is added to the map. This error could have been eliminated by taking flat-field frames away from L134, but would have required significantly more observing time.

Figure 1 is a gray scale representation of the average of the two maps. The bright spot near the upper right-hand corner is the remnant of a bright star which was not completely removed from the frame. The contours plotted in the figure indicate star count densities as determined from the Palomar Sky Survey *E*-plate. For the night on which these observations were made, the night-sky brightness was $\nu I_\nu \approx 3.0 \times 10^{-3}$ ergs cm^{-2} s^{-1} sr^{-1}.

The CCD calibration was obtained by observing several 10th–12th magnitude Landolt standards (Landolt 1983). The calibration constants thus obtained agreed to within a few hundredths of a magnitude for a range of stellar colors and locations on the CCD. The transformation from CCD counts to the physical units of brightness (i.e., ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1}) was accomplished using the absolute calibration of Johnson (1965). The error incurred because of the difference in the Johnson and Landolt passband was small ($\lesssim 10\%$) and was ignored.

b) 2.2 Micron (K band) Observations

K-band ($\lambda = 2.2$ μm, $\Delta\lambda = 0.42$ μm) observations were made at the 1.3 m telescope at Kitt Peak National Observatory in 1981 May and in 1985 April using a standard InSb photometer with 1′ aperture. The difference between the luminosities of the cloud and the blank sky were obtained with an 8 Hz chopping secondary which switched the beam from a position on the cloud to a reference sky position to the east. In order to eliminate offsets, the telescope was moved every 60 s to the west, so that the same position on the cloud was compared with a reference sky position to the west. The distance of the reference position to the main beam was varied from 8′ to 13′ to avoid sources in the reference beam. The difference between these two signals is then proportional to the luminosity of the cloud minus the average luminosities of the two reference positions. The positions on the cloud are shown superposed on a Palomar Sky Survey *E*-print in Figure 2. Also shown are the reference sky positions associated with the darkest cloud positions. In these cases the blank sky regions lay to the northeast and the southwest of the cloud.

The data were taken in blocks either 10 or 20 minutes long. The combined data for each cloud position numbered sequentially from north to south are listed in Table 1. One correction was applied to the data. Because the chop throws were large, the change in airglow due to a secant law atmosphere resulted in a small contribution to the signal. Airglow was determined by monitoring the DC output of the photometer at several zenith angles, and this value was used to correct the data. These corrections were all smaller than the standard deviations listed in Table 1.

K-band calibration was obtained by observing several second through fourth magnitude KPNO infrared standards.

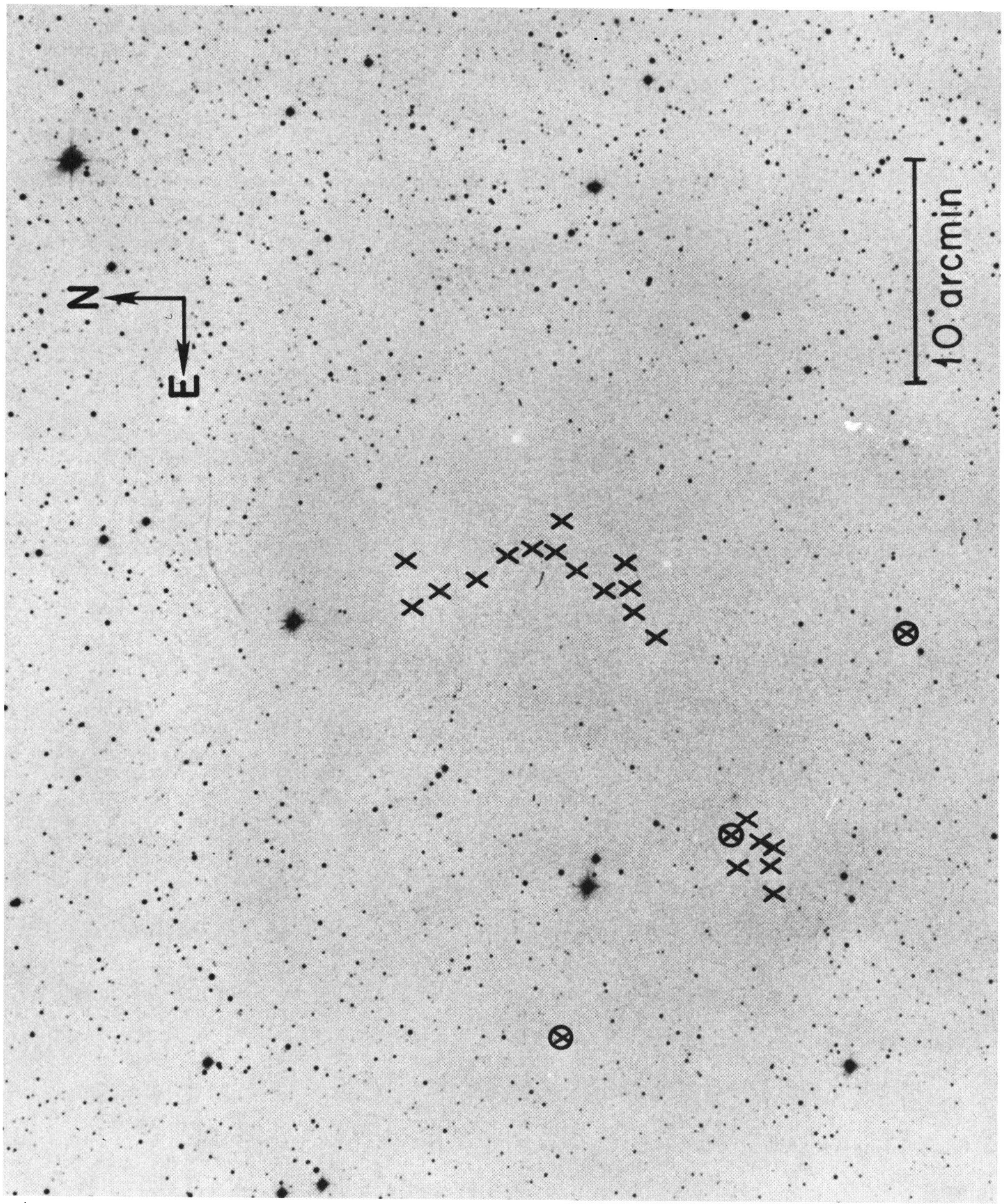

FIG. 2.—Locations of the 21′1 regions superposed on the Palomar Sky Survey *E*-plate. The beam on the cloud and two reference beams are indicated for position 15.

TABLE 1

K-Band Brightness of 1′ Regions on Cloud[a]

Position	νI_ν
1..........	$1.8 \pm 0.3 \times 10^{-4}$
2..........	1.7 ± 0.4
3..........	2.8 ± 0.6
4..........	2.0 ± 0.3
5..........	1.7 ± 0.5
6..........	1.1 ± 0.2
7..........	1.5 ± 0.3
8..........	1.2 ± 0.2
9..........	1.2 ± 0.4
10..........	1.3 ± 0.2
11..........	1.6 ± 0.2
12..........	1.2 ± 0.3
13..........	0.8 ± 0.3
14..........	0.7 ± 0.3
15..........	0.4 ± 0.2
16..........	0.4 ± 0.1
17..........	0.6 ± 0.1
18..........	0.1 ± 0.3
19..........	0.1 ± 0.1
20..........	0.5 ± 0.2
21..........	0.3 ± 0.2

[a] Numbered sequentially from north to south (see Fig. 2).

As with the R-band data, transformation to physical units was accomplished using the absolute calibration of Johnson (1965). Again, errors incurred because of the difference in the Johnson and KPNO passbands were negligible and consequently were ignored.

III. DISCUSSION

It is clear from the data of Figure 1 and Table 1 that L134 is bright at both 0.65 and 2.2 μm relative to blank sky. The offcloud R-band reference point is taken to be delta R.A. = 1′ and decl = 19′ in Figure 1. The average R-band excess brightness of the cloud is $\sim 5 \times 10^{-5}$ ergs cm^{-2} s^{-1} sr^{-1}, while the K-band brightness is 1×10^{-4} ergs cm^{-2} s^{-1} sr^{-1}. Since L134 is a cold (12 K), quiescent cloud with no signs of star-formation activity (Mahoney, McCutcheon, and Shuter 1976), the brightness is presumably due to reflected light from the Galaxy. While there are a few dark regions, notably the dark spot located 26′ east and 20′ north in Figure 1, the general R-band appearance of the cloud is bright near the center and darker near the edges. The usual appearance of an optically thick cloud illuminated from the back, i.e. the Galactic center, is a dark center and bright rim (Witt and Stephens 1974; FitzGerald, Stephens, and Witt 1976). It would seem, therefore, that there is at least some front illumination by the Galactic plane which has a V-band surface brightness near the solar neighborhood of $\sim 5 \times 10^{-4}$ ergs cm^{-2} s^{-1} sr^{-1} (Sandage 1976). Of course, to explain the details of the brightness distribution one must not only know the scattering properties of the dust particles but also the geometry of L134 which may include four dynamically distinct subclouds (Mahoney, McCutcheon, and Shuter 1976).

A Monte Carlo calculation was performed by Gayley (1983) in order to estimate the K-band light scattered from the cloud. The Galaxy light was taken from the 2.4 μm survey of Okuda (1981), and L134 was modeled as a uniform sphere of dust with an optical depth of 1.5 and albedo of 0.6. The result was an average cloud brightness of 1.3×10^{-4} ergs cm^{-2} s^{-1} sr^{-1} which compares favorably with the averaged observed brightness of 1×10^{-4} ergs cm^{-2} s^{-1} sr^{-1}, however, only a rough comparison is warranted by the data and the calculation. Finally, since the K-band measurements were obtained with a single-aperture detector, diffuse light cannot be distinguished from background point sources shining through the cloud.

Because L134 appears everywhere bright compared to blank sky, no unambiguous conclusions can be drawn about the intensity of the diffuse background. However, relative to the background sky, at the darkest positions both the 2.2 and the 0.65 μm intensities are below the current best upper limits of the EBL and may be of some importance. The average K-band intensity of positions in the "toe," i.e., Nos. 16–23 (see Table 1), correspond to an intensity of 3.8×10^{-5} ergs cm^{-2} s^{-1} sr^{-1}, while near the center the average intensity is $\sim 1 \times 10^{4}$ ergs cm^{-2} s^{-1} sr^{-1}. The dark spot near the top center of Figure 1 has an R-band intensity of 1.0×10^{-5} ergs cm^{-2} s^{-1} sr^{-1}. Because the intensity of the dark spot was compared to a nearby region of blank sky (delta R.A. = 1′ and delta decl. = 19′ in Fig. 1), the effect of the spurious gradient in the map mentioned above was negligible. In order to assess the significance of these values as upper limits to the EBL, the extent to which the background is attenuated in the cloud must be estimated.

The optical depth in the central portion of the cloud was estimated in two ways. From Johnson (1964) we have the following approximate relations:

$$A_R/A_B = 0.64 \quad \text{and} \quad A_K/A_B = 0.16 ,$$

where A_R is the extinction in the R band measured in magnitudes, and so on. Since extinction in the blue band was measured by Mattilla (1979) to be $A_B > 9.7$, we conclude that $A_R > 6.2$ and $A_K > 1.7$. In addition, we performed JHK photometry on a star (1950: $15^{\rm h}52^{\rm m}39^{\rm s}.9$ $-4°35′30″$) located behind the center of the cloud. We obtained $m_J = 11.29 \pm 0.05$; $m_H = 9.60 \pm 0.05$; $m_K = 8.90 \pm 0.05$. In order that the star be located at least 150 pc away (the estimated distance to L134) it must either be an early main-sequence star or a giant. The most conservative estimate of the extinction in the cloud is obtained by assuming the obscured star is a late giant. Even if we assume it is as late as M4, the $J - K$ redding is $E_{J-K} = 1.41$. Again from Johnson (1964), we use the approximate relations $A_R/E_{J-K} = 5.0$ and $A_K/E_{J-K} = 1.2$ and conclude that $A_R > 7.1$ and $A_K > 1.7$. One may worry that the dark spot in the R-band map is simply a hole in the cloud. However, no stars are visible on the Palomar red print in this region, and there is significant K-band luminosity there, indicating either reflected light or an obscured source. Either of these two possibilities implies significant R-band extinction.

The optical depth of the cloud as determined from stellar extinction is due to both absorption and scattering by dust particles, while a diffuse background is attenuated only by absorption. It is therefore necessary to estimate the relative contribution of these two effects. Following Mattila (1976), we express the brightness of the cloud due to a diffuse background as the sum of the light which passes directly through the cloud and the light that is scattered; i.e.,

$$L_c = L_0 e^{-\tau} + L_0 f_{\rm scat}(\tau, a, g) ,$$

where L_c is the cloud brightness, L_0 is the brightness of the background, τ is the optical depth, and $f_{\rm scat}$ depends on the optical depth, τ, the albedo, a, and the Henyey-Greenstein asymmetry parameter, g. From numerical calculations, Mattila (1976) estimates that for typical parameter values, $a = 0.5$ and $g = 0.75$, the cloud luminosity L_c is $\sim 0.5\ L_0$ for $\tau = 1.5$. If our estimates of the K-band extinction are accurate, then only about one-half of the K-band background is blocked by the cloud. For $\tau > 6$, $L_c \ll L_0$, and we conclude that the cloud is an effective screen for the K-band background. We can, therefore, offer the following approximate upper limits to the EBL, with the proviso that if the reflected light from L134 and EBL fortuitously cancel, then these limits will be violated:

0.65 μm:

$$\nu I_\nu < 10^{-5}\ {\rm ergs\ cm^{-2}\ s^{-1}\ sr^{-1}}\ .$$

2.2 μm:

$$\nu I_\nu < 10^{-4}\ {\rm ergs\ cm^{-2}\ s^{-1}\ sr^{-1}}\ .$$

IV. CONCLUSIONS

The tentative upper limits to the EBL, although lower than previous limits, are still slightly larger than the predictions of some of the models of Partridge and Peebles (1967*a*, *b*) and Tinsley (1977); however, it should be emphasized that there is a great deal of uncertainty in these models.

Perhaps a more significant result of the present observations is that large-field ($\sim 1°$ across), R-band surface photometry with a CCD can be performed at intensities of 0.1% of the night sky. The mosaicking technique described above should be useful in investigating extended sources of diffuse radiation such as the intergalactic light predicted to exist in rich clusters of galaxies (Melnick, White, and Hoessel 1977; Dressler 1984) or surveying high Galactic lattitudes to determine the quantity of dust and, therefore, extinction out of the plane (Sandage 1976).

The possible use of dark molecular clouds in measuring the magnitude of the EBL is still an open question. This paper has suggested that at 0.65 μm dense clouds have relatively dark spots which are presumably due to shadowing of galactic light by foreground regions. Alternatively, a search for spatial anisotropy in wide-angle blank fields is practical and might more easily yield evidence for EBL.

The situation at 2.2 μm is more problematic. Clouds seldom have large optical depths at this wavelength, so it is less likely that dark regions can be found. The lack of an imaging detector also complicates the interpretation of such measurements (it is notable that short-wave IR detector array technology is rapidly improving).

We are grateful to E. Wright for pointing out the existence of the background star, and to D. T. Wilkinson and M. S. Seldner, who helped obtain early IR observations and for numerous useful discussions. The star counts indicated in Figure 1 were compiled by C. Valdez. This research was supported in part by the National Science Foundation.

APPENDIX

SKY BACKGROUND FITTING PROCEDURE

Let $d_i(\boldsymbol{r})$ represent the observed brightness at some sky location, $\boldsymbol{r}$, as obtained in the ith CCD frame (or "window"). Here we assume $\boldsymbol{r}$ is a vector that discretely parametrizes all pixel locations across the field. Our aim is to fit the data from all windows ($i = 1, \ldots, N$) as

$$d_i(\boldsymbol{r}) \rightarrow a_i + b(\boldsymbol{r})\ , \tag{A1}$$

where a_i is a window dependent offset (like a variable airglow that changes between frames) and $b(\boldsymbol{r})$ is the actual (constant) sky signal. In general, we can hope for a simple model like this to yield useful results only when secant law variations across a window are small and when the spatial scale for airglow variations is much larger than the scale of a single window. We will use the fact that frames overlap (that is, any point specified by $\boldsymbol{r}$ will be observed in at least two windows) to construct a mosaic of relative photometric measurements accurate over the field of all overlapping windows.

Let $W_i(\boldsymbol{r}) = 0$ if there is no observation in window i at $\boldsymbol{r}$, and 1 otherwise; let this function describe the sky points that are sampled by the ith window. Notice that, in general, W describes the position in the sky of a particular frame and carries information about where data are to be ignored, e.g., where they are due to bright objects as discussed in § II. Then an efficient procedure to fit the model of equation (A1) is to minimize the summed squared errors between the model and all data:

$$\sum_{\boldsymbol{r}} \sum_i \{d_i(\boldsymbol{r}) - W_i(\boldsymbol{r})[a_i + b(\boldsymbol{r})]^2\}^2 \tag{A2}$$

with respect to the unknown quantities a_i and $b(\boldsymbol{r})$. Notice that there are N unknown values a_i and one value of $b(\boldsymbol{r})$ at each sky location in the field to be determined. For the 32 overlapping windows we used to map L134 the parameters are highly overconstrained. Let N_i equal the total number of valid observations (pixels) in window i, $N(\boldsymbol{r})$ be the number of observations of the sky point $\boldsymbol{r}$ over all windows, and $\langle d(\boldsymbol{r})\rangle_w = \sum d_i(\boldsymbol{r}) W_i(\boldsymbol{r})/N(\boldsymbol{r})$ be the average of the data using all windows. Minimization of equation (A2) yields

$$C_{ij} a_j = \sum_{\boldsymbol{r}} [d_i(\boldsymbol{r}) - \langle d(\boldsymbol{r})\rangle_w] W_i(\boldsymbol{r})\ , \tag{A3}$$

with

$$C_{ij} = N_i \delta_{ij} - \sum_{\boldsymbol{r}} W_i(\boldsymbol{r}) W_j(\boldsymbol{r})/N(\boldsymbol{r})$$

for the parameters a_i and with repeated indices summed over. The correlation matrix C_{ij} is obviously symmetric, but unfortunately it can also be shown to be singular. The singularity is expected and is due to an obvious symmetry: adding a constant to all the a_i of a valid solution yields another solution. This problem is solved by setting $a_k = 0$, which yields a new $N - 1 \times N - 1$ matrix C_{ij} which has an inverse. The solution for the remaining a_i follows directly from equation (A3). The final mosaic is obtained by correcting the d_i by the parameters a_i and then properly averaging the overlapping frames to obtain the best least-squares estimate of $b(\boldsymbol{r})$.

The practical limitations of the technique seem to come from secant law variations of the airglow and residual errors in the flat-fielding procedure. Because our flat fields were obtained from averages of the cloud observations, our relative photometry suffers from a systematic gradient comparable to the rms gradient in the actual cloud data frames. This was larger than the secant law error, as discussed above. In principle, simple modifications of equation (A1) to include a frame-dependent secant law correction are straightforward, but unnecessary in this case because of the larger specific flat-fielding errors.

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